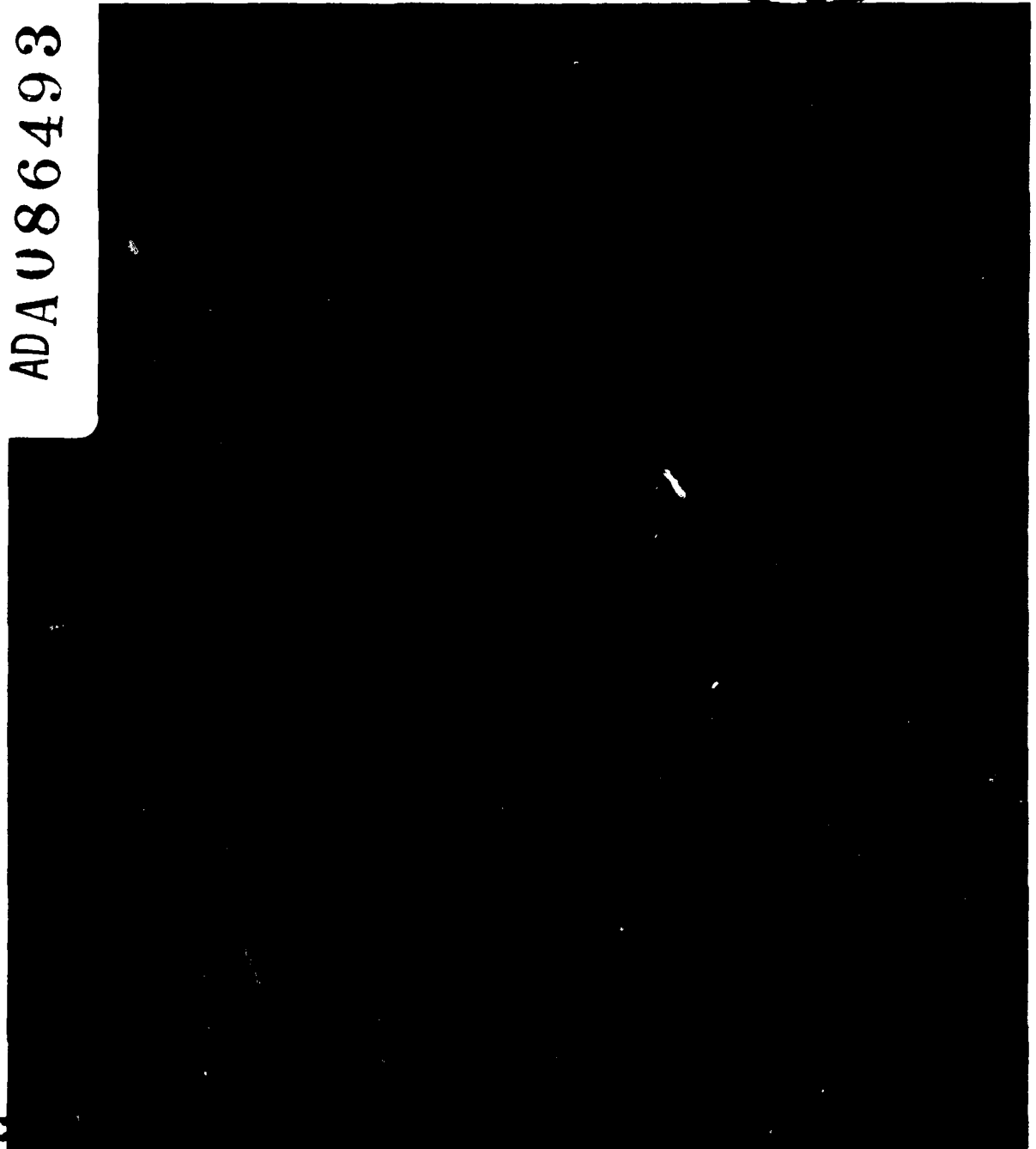END

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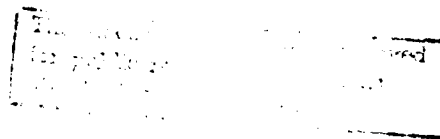
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements of front velocity and transported electron beam current are reported for several configurations of dielectric guide. It appears that the ions which determine the speed of beam-front propagation come only from a short section of dielectric near the inlet of the guide. They are accelerated in the potential well of the virtual cathode formed when the space-charge-limited electron beam is injected. Plasma formed by electron bombardment of the down-stream guide walls apparently does not influence the beam-front speed, although it is important in determining the efficiency of current transport. Measurements,

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20. Abstract (Concluded)   :

of collective ion acceleration have been deferred until the second year of the
program.

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LIST OF FIGURES

FOREWORD

The authors wish to acknowledge the contributions of Paul F. Meroth and Stephen L. Achorn in preparing and executing the experiments described in this report.

SECTION 1

INTRODUCTION

This report summarizes the research performed by Spire Corporation during the first year of the program, "Collective Ion Acceleration and Electron Beam Propagation in Dielectric Guides". During this period the study was concentrated on the propagation of electron beams in evacuated dielectric guides of various configurations. This emphasis was based on our belief that an understanding of the physical mechanisms involved in the transport of high-current electron beams (far exceeding the space-charge-limited current) in dielectric guides is required to understand the related phenomenon of collective ion acceleration.

In these experiments Spire's SPI-PULSE 600 accelerator was used to inject pulsed electron beams with energies between about 70 and 200 keV and currents between 5 and 20 kA into evacuated dielectric guides. Measurements of the speed of propagation of the beam front and the transmitted electron current were made as a function of accelerator parameters and guide configuration. Cylindrical guides of various geometries and a conical guide provided the source of neutralizing ions; the ions are formed by inelastic collisions between the space-charge-limited electron beam and desorbed gas and by surface and volume breakdown at the walls of the guide. The neutralizing ions, principally protons, are accelerated by the potential well of the virtual cathode formed by the intense electron beam. The depth of the potential well is equal to, or somewhat greater than, the instantaneous voltage on the electron accelerator. As discussed in Section 2, we expected the front velocity to scale as the speed of a proton accelerated in this well, or proportionally to $E^{1/2}$, where E is the electron beam energy.

As reported in Section 3, we found that the front velocity was essentially independent of all parameters which were varied in the experiments. Although there seems to be gross scaling of beam-front velocity with the square root of electron energy, detailed measurements do not show a significant variation over the range available with our accelerator. This result, together with strong evidence of gross scaling of beam-front velocity with $E^{1/2}$, leads us to a model in which the neutralizing ions are launched downstream in the guide before the potential well reaches its maximum value. Plasma generated at the walls of the guide by electron impingement from the partially neutralized head of the beam only aid in the transport of current once the beam front has passed.

As discussed in Section 4, this model is supported by one-dimensional computer simulations and our measurements of transported electron current, which show losses both by beam-front erosion and an exponential decrease of current with guide length. These transport measurements were made in high-dielectric-strength epoxy guides, which apparently provide enough ions at the inlet to initiate beam-front propagation, but not enough downstream to support the full current of the injected electron beam.

Plans for the next year of the program are summarized in Section 5 of this report.

SECTION 2
BACKGROUND

2.1 GENERAL

The phenomena of electron beam propagation and collective ion acceleration in evacuated dielectric guides were discovered several years ago at Spire Corporation by Little, Greenwald, and others.[1,2,3] The model of beam propagation at currents much larger than the space charge limit is shown in Figure 2-1.

A high-current, pulsed electron beam is accelerated through the anode of a field-emission diode into the evacuated dielectric guide. The beam quickly forms a virtual cathode a short distance from the anode, and the following electrons are reflected and spread radially by the electric field of the virtual cathode until they impinge on the wall of the dielectric guide. A low-temperature plasma is formed at the irradiated surface of the guide by various processes, including volume breakdown of the dielectric, surface flashover, and ionization and breakdown of desorbed gas. The ions of this plasma are accelerated electrostatically into the virtual cathode, where they partially neutralize the electronic space charge. The electron beam can now propagate down the guide until it leaves the neutralized region; when this happens, the beam again expands and repeats the process of plasma formation and neutralization. The beam propagates in this manner until the beam front reaches the end of the guide or the injected current from the diode is cut off.

Collectively accelerated ions, principally protons, have been observed in several experiments on propagating electron beams in dielectric guides.[4,5,6] Two groups of ions have been registered. The first group apparently has velocities equal to that of the propagating front and energies approximately equal to the energy of the accelerated electron beam. The second group has energies of 3 to 10 times the energy of the electron beam and is only observed under conditions of high injected electron current and rather poor propagation of the electron beam. The origin of the high-energy ions is not understood and is presently under study in several laboratories.

- ~$^2/_3$ Q_{INJ} HITS THE WALL EARLY

- VOLTAGE BUILDS UP

a

- FLASHOVER OCCURS
    −IONS RELEASED

- IONS ACCELERATED INTO CAVITY − SPACE-CHARGE NEUTRALIZE

b

- PROCESS REPEATS FURTHER DOWN THE CAVITY UNTIL
    − REACHES END
    − OR NO MORE ELECTRONS

c
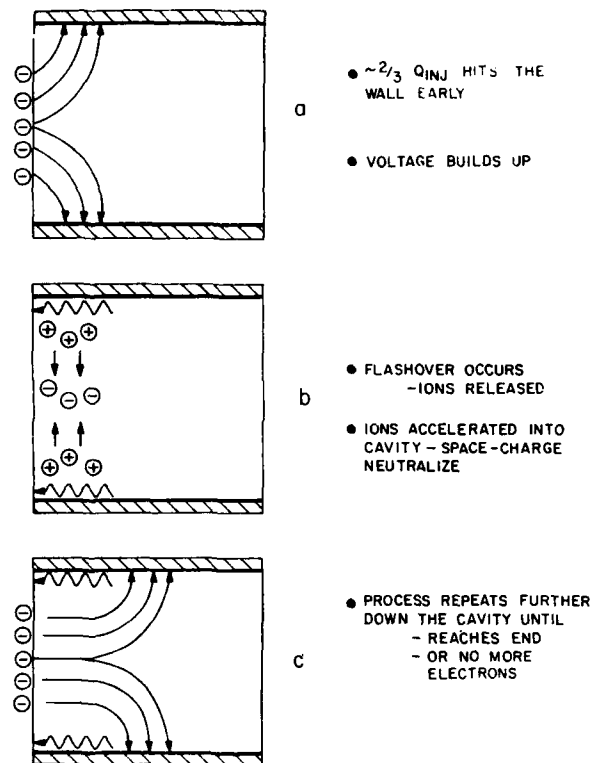
FIGURE 2-1. MODEL OF ELECTRON BEAM PROPAGATION
IN EVACUATED DIELECTRIC GUIDE

2.2 ELECTRON BEAM PROPAGATION

In earlier experiments at Spire and elsewhere, it was shown that the electron beam current was efficiently transported down the dielectric guide; up to 80 percent of the injected current could be transmitted for distances of 20 to 30 cm in dielectric cylinders, and similar results, with somewhat poorer transmission of current, have been observed in dielectric cones.[7]

The transported electron current appears to propagate behind a sharply defined "front" region where, in our qualitative model, the beam is no longer neutralized and is impinging on the wall of the guide. The unneutralized beam current far exceeds the space charge limit under these conditions and forms a virtual cathode near the front. The speed of the front has been shown to be independent of the guide material, guide diameter, and ratio of cathode-to-guide diameter for several experimental

configurations. The speed of the front shows some correlation, however, with the peak energy of the accelerated electrons. Figure 2-2 shows the range of measured beam-front velocities as a function of electron energy for experiments in four different laboratories. The solid line indicates the velocity of a proton accelerated to the same energy, E, as the electron beam. Although individual experiments show little variation of the front velocity with electron energy, a rough $E^{1/2}$ scaling of the speed of the front seems to be indicated.

FIGURE 2-2. MEASUREMENTS OF BEAM-FRONT VELOCITIES IN DIELECTRIC GUIDES AS A FUNCTION OF ACCELERATED ELECTRON ENERGY (References: Spire[1], NRL[5], Lebedev[6], NCSU[8].)

2-3

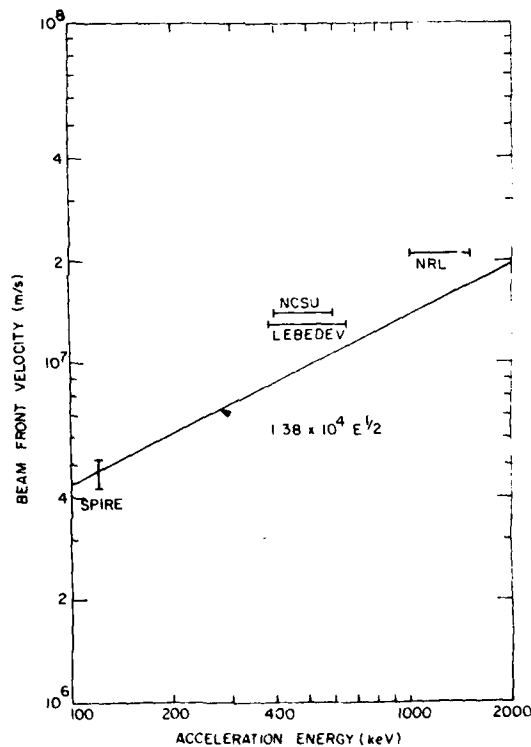The scaling of the front velocity and the approximate constancy of this velocity with experimental configuration are qualitatively similar to measurements of beam propagation and collective ion acceleration in "Luce diodes"[9] and to experiments at the University of Maryland[10] in which relativistic electron beams were injected into a puff of gas near the anode of the accelerator. Similar results have been reported on experiments in which pulsed electron beams were accelerated into thin plastic foil anodes[11] and nearly constant velocities of the propagating beams were measured. Collectively accelerated ions with energies several times the electron energy were also observed in these experiments.

One-dimensional calculations and computer simulations of the propagation of electron beams indicate that the fronts of relativistic electron beams neutralized near the anode should scale as the velocity of the neutralizing ions, which have an energy of about that of the electron beam. A high-energy tail of the ion velocity distribution has been seen in one-dimensional computer simulations[11] as well as time-dependent phenomena such as high-frequency pulsations.[12]

A basic question which was addressed during the first year of this program was the detailed variation of the beam-front velocity with experimental parameters. It seems unlikely that a rough dependence of this velocity on a fundamental parameter such as beam energy should not also be followed in detailed measurements.

Another question which has not been answered for electron beams propagating in evacuated dielectric guides concerns the role of the guide downstream from the anode region. It is possible that the observed independence of the propagation speed of the beam front with guide diameter and material is a result of phenomena occurring at the time of the neutralization of the initial virtual cathode. Plasma formed downstream from the anode may only serve as a neutralizing medium for the propagating beam once the unneutralized front has passed.

SECTION 3
EXPERIMENTAL PROGRAM

3.1 APPARATUS

3.1.1 Electron Accelerator

All of the present experiments were conducted using the SPI-PULSE 600 electron accelerator, which is a 9-ohm solid-dielectric transmission line, statically charged by a Van de Graaff generator to voltages up to 400 kV. The line is discharged by a spark switch into a field-emission diode, producing an approximately 40-ns pulse with energies up to 200 keV and currents of 22 kA when the diode impedance is matched to the line. Adjustments to the cathode diameter and the anode-cathode spacing produce a variety of beam parameters, from high-energy, low-current beams with overmatched diodes to low-energy, high-current beams when the diode impedance is considerably less than the 9-ohm line impedance.

Figure 3-1 shows the SPI-PULSE 600 accelerator and its control console. The Van de Graaff generator is located in the large cylindrical vessel at the left; the 9-ohm charged transmission line is in the long cylinder, which is a pressure vessel for the dielectric gas used for the suppression of corona and premature switch breakdown. The switch and field-emission diode are located at the end of the charged line at the extreme right of Figure 3-1.

The field-emission diode of the accelerator is a textured graphite cathode located at the end of the switch assembly and a partially transparent anode mesh at ground potential. The anode is replaceable by meshes of different opacity or by metallic foils. The diode region is evacuated to a pressure in the range of 10^{-4} torr by an oil diffusion pump, which also evacuates the chamber in which the dielectric guides and beam diagnostics are located.

Table 3-1 gives the characteristics of the SPI-PULSE 600 accelerator under typical operating conditions.

3.1.2 Diagnostics

The principal diagnostics used in the beam propagation experiments were a movable Faraday probe and the voltage and current monitors of the electron accelerator. The Faraday probe was inserted inside the dielectric guides to measure the
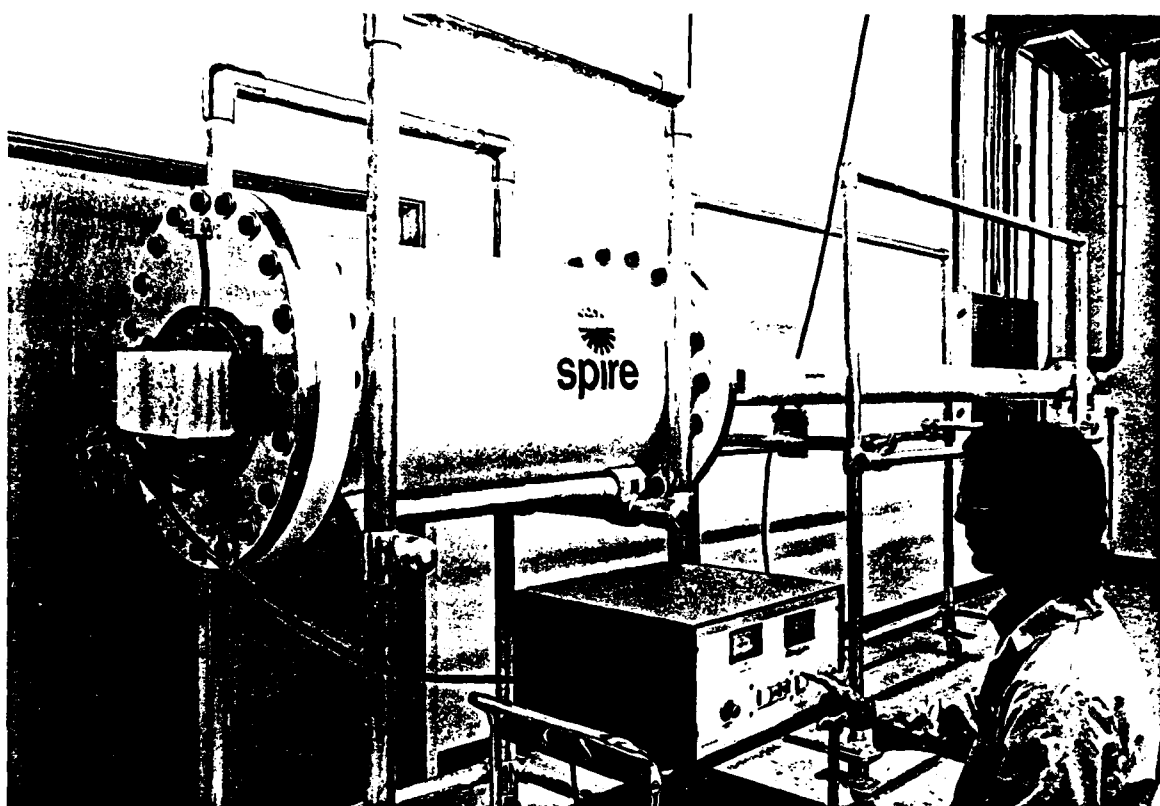
FIGURE 3-1. SPI-PULSE 600 ELECTRON ACCELERATOR

TABLE 3-1. CHARACTERISTICS OF SPI-PULSE 600 ELECTRON ACCELERATOR

CHARGED LINE

Capacitance	1.9 nF
Impedance	9 ohms
Electrical length	40 ns

ELECTRON BEAM

Charging Potential (kV)	Cathode Diameter (mm)	A-K Gap (mm)	Beam Voltage (kV)	Beam Current (kA)
150	38	3.5	70	7
300	38	3.5	140	16
300	38	7	180	9
300	76	3.5	120	22
400	38	3.5	190	22

arrival time of the beam front and the total transmitted current as a function of axial position in the guide. The probe was a 5.1-cm-diameter aluminum plate grounded through a 0.26-ohm resistor; in some experiments the probe was shielded by a 6-micrometer-thick aluminum foil to suppress signals from electrons and ions of the low-temperature plasma formed at the walls of the guide.

The temporally resolved characteristics of the electron beam were measured by a capacitive voltage monitor and a current shunt mounted on the diode of the electron accelerator. The signals from these diagnostics were displayed for every shot on high-frequency Tektronix 519 oscilloscopes. Figure 3-2 is a schematic diagram of the diode region of the accelerator and also shows a cylindrical dielectric guide and the movable Faraday probe.

An attempt was made to measure the beam current and arrival time of the propagating front using small magnetic loops mounted on the outside of the dielectric guide. This measurement was not successful because electrical noise picked up on the loops completely obscured any signal induced by the propagating beam. It is likely that this interference originated in the field-emission diode, although noise generated at the surface of the guide by the processes of plasma formation may also have been a major contributor.
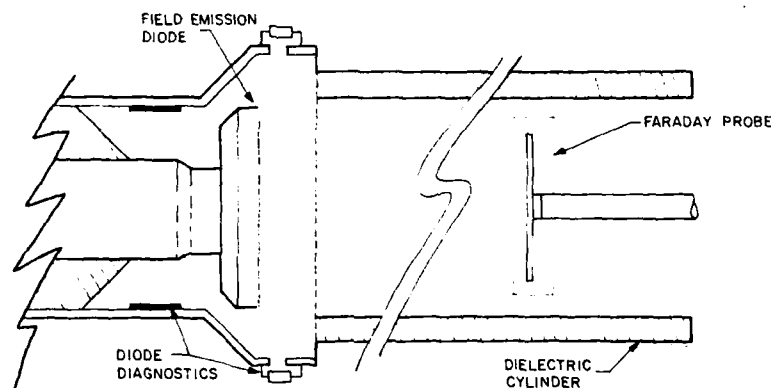
FIGURE 3-2. SCHEMATIC OF FIELD-EMISSION DIODE AND DIAGNOSTICS

3.1.3 Dielectric Guides

Cylindrical guides of two materials and various diameters and lengths and a conical guide were used in the beam propagation experiments. Table 3-2 gives the characteristics of the guides used in these experiments.

The material of the cast epoxy guides, E&C Stycast 1264, has a dc dielectric strength greater than 3 MV/cm and a high-frequency dielectric constant of 3.3.

The guides were mounted in an aluminum vacuum chamber which is an extension of the vacuum housing for the diode of the accelerator. The anode end of the guides must be held in close mechanical contact with the anode mesh to assure good injection of the beam into the guide. In cases where there was poor contact, tracking was observed across the surface of the dielectric to the grounded anode support, and low currents were registered on the Faraday probe.

TABLE 3-2. DIELECTRIC GUIDES

CYLINDRICAL

Material	I.D. (cm)	Wall (cm)	Length (cm)
Epoxy*	6	1.3	3.6
Epoxy*	6	1.3	20
Lucite (Poly-methylmethac-rylate)	8.3	0.6	30

CONICAL

Material	I.D. (cm)		Wall (cm)	Length (cm)
	Inlet	Outlet		
Epoxy*	6.7	1.3	1.0	20

*Stycast 1264, Emerson and Cuming, Inc., Canton, MA.

3.2 RESULTS

Figure 3-3(a) shows typical diode voltage and current traces for experiments with a 3.8-cm-diameter cathode and a 3.5-mm anode-cathode gap. At an initial charging voltage of 300 kV the diode impedance is nearly matched to that of the 9-ohm line. The anode mesh had an optical transparency of 78 percent for these experiments, and if we assume that this fraction of the diode current was transmitted, then about 12 kA of electrons with an energy of 145 keV were injected into the guide.

Figure 3-3(b) shows recordings of the current measured by the Faraday probe at positions of 2 cm and 15 cm from the anode in the cylindrical epoxy guide of 6-cm diameter and 20-cm length. The long "tail" of the current pulse at the 2-cm position probably is caused by electrons from the background plasma which penetrate the 6-micrometer aluminum foil through small holes.

VOLTAGE   CURRENT

140 kV   18 kA

50 ns   50ns

(a) E-BEAM DIODE

5 kA   2 kA

50 ns   50ns

Z = 2 cm   Z = 15 cm

(b) TRANSMITTED CURRENT

EPOXY GUIDE
l ≈ 6 cm
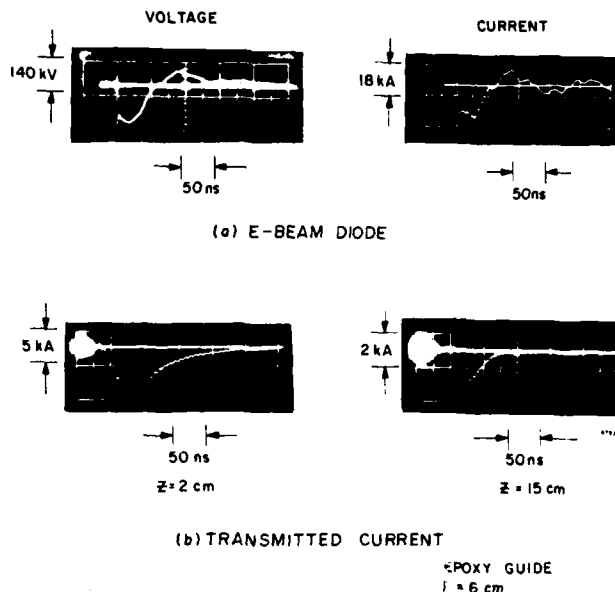
FIGURE 3-3.   (a) DIODE VOLTAGE AND CURRENT OF SPI-PULSE 600
UNDER TYPICAL EXPERIMENTAL CONDITIONS AND
(b) TRANSPORTED BEAM CURRENT AT POSITIONS OF
2 cm AND 15 cm DOWN GUIDE

It can be seen in Figure 3-3(b) that the transmitted current pulse is shortened by beam-front erosion and the peak current is reduced by about a factor of four between the 2-cm and 15-cm positions.

In earlier experiments, Spire and other groups found that beam-front erosion represented the principal loss of charge from the transmitted beam, and nearly all the injected current was transmitted behind the beam front. Further evidence of this discrepancy is discussed in Section 3.2.2.

3.2.1 Beam-Front Velocity

Cylindrical Guides

A series of experiments was conducted to test the dependence of the beam-front velocity on electron energy and other experimentally controllable parameters. The beam energy was varied both by changing the charging voltage on the accelerator and by varying the impedance of the diode.

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Figure 3-4 shows the arrival time of the beam front as a function of the axial position of the Faraday probe in the 20-cm-long by 6-cm-diameter cylindrical epoxy guide. The beam energy was varied by changing the charging voltage on the accelerator from 150 kV to 400 kV. The diode was operated with a 3.8-cm-diameter cathode and a 3.5-mm anode-cathode gap. The maximum current injected into the guide for the 190-keV beam was 17 kA; the maximum current at 73 keV was 5.5 kA.

The effect of varying the current injected into the dielectric guide was studied by replacing the 78 percent transmitting tungsten anode mesh by a 36 percent transmitting stainless steel mesh. A constant charging voltage of 300 kV was used in these experiments, and the diode parameters were the same as for Figures 3-3 and 3-4. The results of this test are plotted in Figure 3-5, showing no significant difference in the velocity of propagation of the beam front for variations of the injected electron current of almost a factor of two.
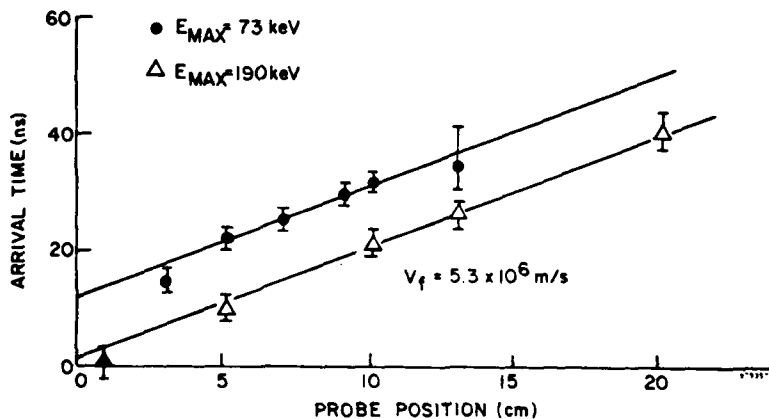
FIGURE 3-4.   BEAM-FRONT ARRIVAL TIME VERSUS POSITION OF FARADAY PROBE IN CYLINDRICAL EPOXY GUIDE FOR TWO ELECTRON INJECTION ENERGIES
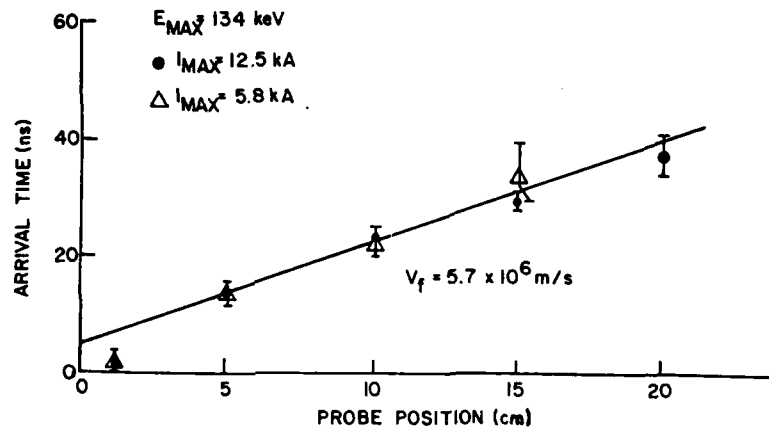
FIGURE 3-5. BEAM-FRONT ARRIVAL TIME VERSUS PROBE
POSITION IN CYLINDRICAL EPOXY GUIDE
FOR TWO VALUES OF INJECTED CURRENT

A series of measurements of beam front arrival times was performed in a cylindrical Lucite (polymethylmethacrylate) guide of 30-cm length and 8.7-cm inside diameter. Figure 3-6 shows results of these experiments for an accelerator charging voltage of 300 kV, a diode gap of 3.5 mm, and two cathode diameters, 3.8 cm and 7.6 cm. The accelerator produced a 140-keV, 12.5-kA beam with the 3.8-cm-diameter cathode and a 120-keV, 17-kA beam with the 7.6-cm-diameter cathode. The slope of the time-position curve is about the same under both operating conditions, although the arrival times of the front appear to be perturbed by the presence of the Faraday probe under higher current conditions.
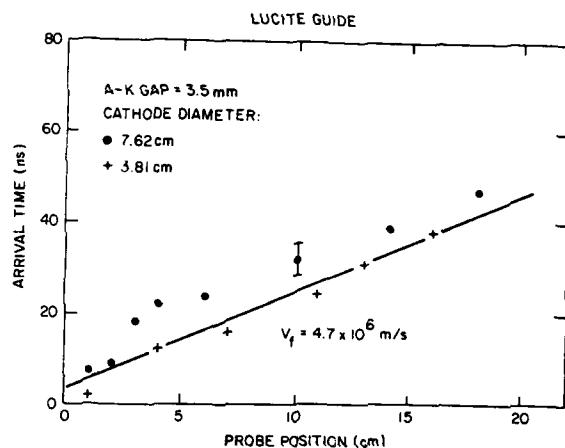
FIGURE 3-6. BEAM-FRONT ARRIVAL TIME VERSUS PROBE
POSITION IN LUCITE GUIDE

Short Cylindrical Guide

As a test of the influence of the length of the guide on electron beam propagation, the 6-cm-diameter epoxy guide was cut to a length of 3.6 cm, and beam-front arrival times measured as a function of axial position. Experiments were made with 300-kV initial charging voltages, a 3.8-cm-diameter cathode, and anode-cathode gaps of 3.5 mm and 7 mm. The 7-mm gap produced a beam of 180-keV peak energy and 5 kA transmitted into the guide.

Figure 3-7 shows the arrival time of the beam front as a function of Faraday probe position for the 3.6-cm-long epoxy guide and a 3.5-mm anode-cathode gap. For comparison, the data of Figure 3-5 for the 20-cm-long guide are repeated in this figure. The propagation speed of the front considerably downstream from the end of the shortened guide is about the same as when the walls of the guide are present.

3-9

FIGURE 3-7. BEAM-FRONT ARRIVAL TIME VERSUS PROBE POSITION IN EPOXY GUIDES UNDER MATCHED DIODE CONDITIONS

Figure 3-8 shows arrival times of the beam front in the 3.6-cm-long and 20-cm-long epoxy guides under conditions in which the anode-cathode was 7 mm and other parameters were the same as in Figure 3-7. Again, it is apparent that speed of propagation does not depend on the presence of the dielectric walls of the guide.

Conical Guide

Beam-front arrival times were measured as a function of axial position in the conical guide, which converged from a diameter of 6.7 cm to 1.3 cm in a distance of 20 cm. An unshielded Faraday probe with a diameter of 1.2 cm was used for these experiments; the diameter of the probe was smaller than that used for the cylindrical guides, so that measurements could be made in the narrow section of the cone.
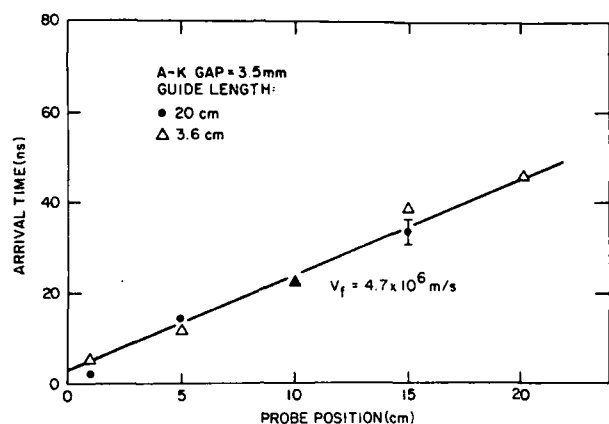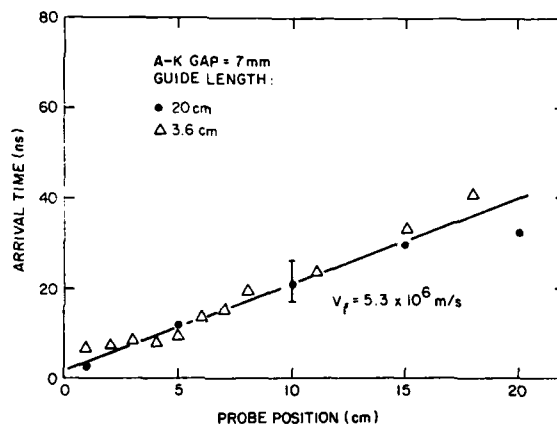
FIGURE 3-8. BEAM-FRONT ARRIVAL TIME VERSUS PROBE
POSITION IN EPOXY GUIDES UNDER
HIGH-IMPEDANCE DIODE CONDITIONS

Figure 3-9 shows the arrival times of the beam front in the conical guide for an accelerator charging voltage of 300 kV, a 3.8-cm-diameter cathode and anode-cathode gaps of 3.5 mm and 7 mm. Under these conditions the propagation speed is about 4×10^6 m/s, regardless of gap setting.

3.2.2 Propagated Current

Measurements of current propagation in the dielectric guides were complicated by three factors. First, the Faraday probe collected not only the transmitted electron beam but also electrons from the low-energy plasma formed at the walls of the guide. This spurious signal was largely suppressed by the 6-micrometer grounded aluminum foil placed over the collector of the probe, as indicated in Figure 3-2, although some leakage current was detected when the probe was placed close to the anode mesh. Second, a considerable amount of the electron beam current can be lost through surface discharges

3-11

CONICAL GUIDE

A – K GAP :
• 3.5 mm
△ 7 mm

$V_f = 4.2 \times 10^6$ m/s

ARRIVAL TIME (ns)
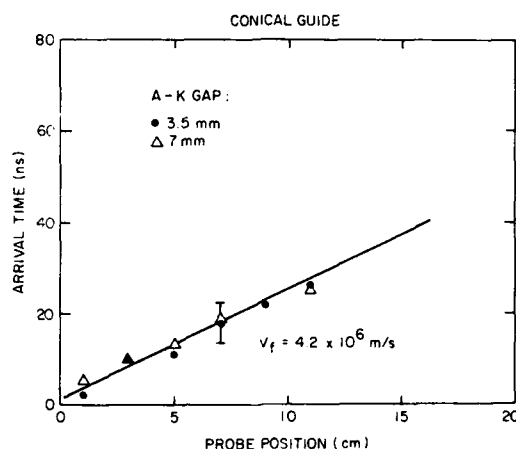
PROBE POSITION (cm)

FIGURE 3-9.   BEAM-FRONT ARRIVAL TIMES VERSUS PROBE
POSITION IN CONVERGING CONICAL GUIDE

across the anode end of the guide when the dielectric is not in good physical contact with the anode mesh. It was found that, although beam-front arrival times were quite reproducible from one experimental setup to another, measurements of the transmitted current were not reproducible if the apparatus was disturbed between experiments. It appears that a fraction of the current injected into the guide was always lost directly to the anode structure, even when the guide was carefully fitted to the mesh. Reasonably consistent measurements of transmitted beam current could be made if the guide and diode were not disassembled during a series of experiments. Third, the presence of the Faraday probe at positions less than 3 or 4 cm from the anode caused perturbations of the current flow under some conditions. This effect was particularly evident for beams accelerated in high-impedance diode configurations. As an example, Figure 3-10 shows the peak transmitted current measured during experiments with the cylindrical epoxy guides, a charging voltage of 300 kV, and a 3.8-cm-diameter cathode and 7-mm anode-cathode gap.

GUIDE LENGTH :
• 20 cm
△ 3.6 cm

PEAK TRANSMITTED CURRENT (kA)

PROBE POSITION (cm)
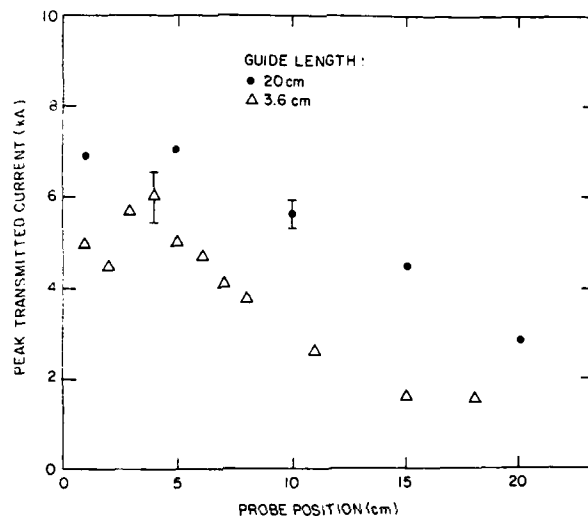
FIGURE 3-10. PEAK TRANSMITTED BEAM CURRENT VERSUS
POSITION OF FARADAY PROBE IN CYLINDRICAL
EPOXY GUIDES

It appears that the Faraday probe is responsible for the reduction of the measured current at axial positions of 4 cm or less by aggravating the surface discharges across the anode end of the guide.

The lack of reproducibility of the measurements of transmitted current between experimental setups led us to plot the peak transmitted current normalized to the current measured at a probe position of 1 cm from the anode. Figure 3-11 shows this plot for the cylindrical epoxy guides of 3.6-cm and 20-cm lengths and for the convergent conical guide. An initial charging voltage of 300 kV and a diode of 3.8-cm diameter and 3.5-mm gap were used for the accelerator.

3-13
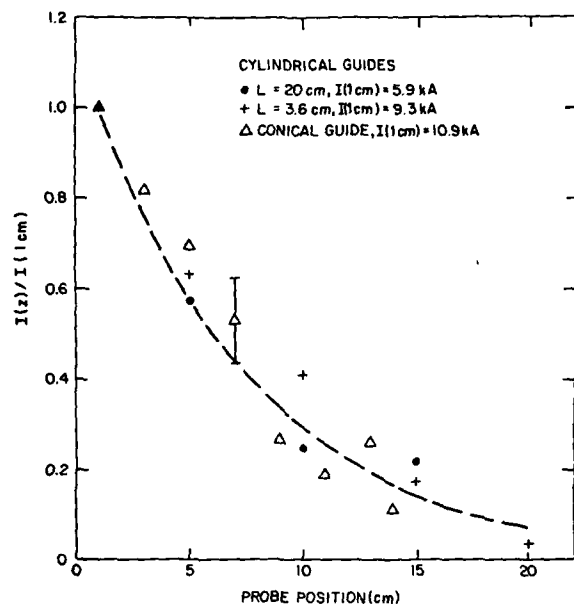
FIGURE 3-11.   NORMALIZED TRANSMITTED BEAM CURRENT VERSUS
PROBE POSITION IN EPOXY GUIDES

The normalized propagating current appears to follow an approximately
exponential decrease with distance down the guide. The dashed curve in Figure 3-11
illustrates a law of the form,

$$\frac{I(z)}{I(1 \text{ cm})} = \exp\left(- \frac{z - 1 \text{ cm}}{7.4 \text{ cm}}\right)$$

The loss of beam current with guide length occurs in spite of evidence of pinching
of the propagating electron beam. Figure 3-12 shows the damage to the 6-micrometer
aluminum foil shield of the Faraday probe after one shot from the electron beam. The
probe was at a distance of 2 cm from the anode, the accelerator was charged to a
voltage of 300 kV, and the cathode diameter and anode-cathode gap were, respectively,
3.8 cm and 7 mm. Similar evidence of beam pinching was observed at all axial positions
in the guide and accelerator conditions.

3-14

7 cm

FIGURE 3-12. DAMAGE TO ALUMINUM SHIELD OF FARADAY PROBE

SECTION 4
DISCUSSION

4.1 BEAM-FRONT VELOCITY

Figure 3-4 indicates that the beam-front velocity, based on measurements of the time of arrival of the current transmitted to the Faraday probe, seems to be a constant 5 x 10^6 m/s, for peak electron energies between 70 and 190 keV. The speed of a proton accelerated to the same energies wou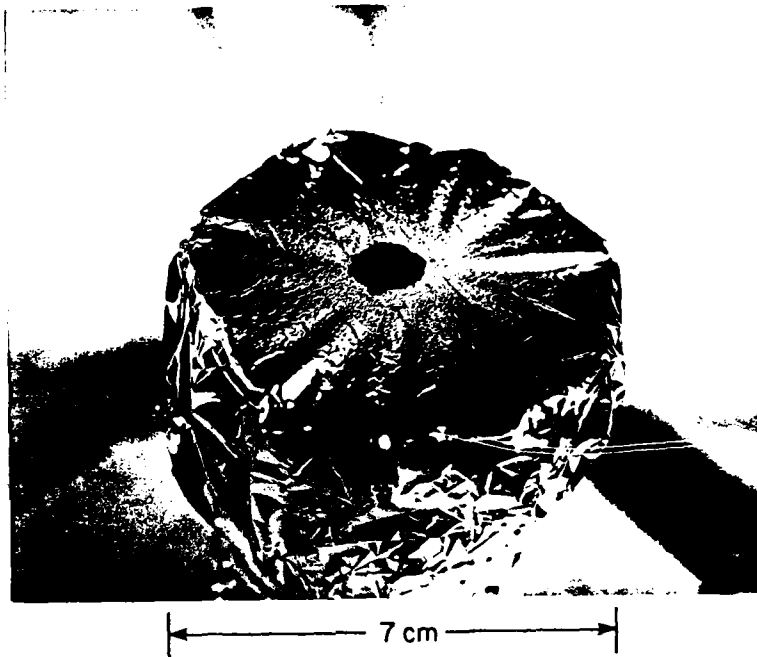ld be 3.7 x 10^6 m/s to 6.0 x 10^6 m/s. A variation of this magnitude in the speed of the front would have been detected in these experiments, so we must conclude that the front velocity does not show a detailed scaling with the square root of the electron energy, $E^{1/2}$.

At a constant acceleration voltage, a factor-of-two change in the current and current density injected into the guide makes no significant change in the speed of the front, as shown in Figure 3-5. Under these circumstances, the peak injected current of 12.5 kA was close to the Alfven limit of 13.1 kA, whereas at 5.8 kA, the injected current was still considerably greater than the space-charge-limited current of about 200 A.

A change of the guide material from a high dielectric strength epoxy to Lucite, which has considerably more hydrogen available for neutralizing the space charge of the electron beam, makes no appreciable change in the speed of propagation of the beam front, as shown in Figure 3-6. A velocity of about 5 x 10^6 m/s was again observed with both matched and high impedance diode settings.

The speed of beam-front propagation does not depend on the actual presence of a dielectric guide, once the beam has propagated a few centimeters, as demonstrated in Figures 3-7 and 3-8. It is reduced less than 20 percent when a converging conical guide is substituted for the cylindrical configuration (Figure 3-9). Agafonov et al. of the Lebedev Institute also found that the front speed of a 500-keV electron beam injected into an cylindrical metallic guide with a 5-cm-long dielectric insert at the inlet was identical to that in a purely dielectric guide.[6]

These results indicate that the processes which determine the velocity of the front act principally near the anode, where the electron beam initially forms a virtual cathode. Under the conditions of this experiment, and very probably that of Agafonov et al., the walls of the guide downstream from the anode do not influence the propagation of the beam front, although there is strong evidence that the efficiency of current transport is influenced by the wall (see Section 4.2).

The apparent independence of the beam-front velocity from the conditions downstream of the inlet to the dielectric guide is similar to the behavior of experiments with "Luce diodes" and other high-current, pulsed electron accelerators in which a dielectric material or gas is placed in the anode region to provide space charge neutralization[9,10,11,13]. Several experiments of this type show that the beam propagates as a sharply defined front associated with energetic ions accelerated to the electron energy or a few times greater.

One-dimensional computer simulations have been used to study the propagation of electron beams ejected into an evacuated volume from an anode which is covered with a sheet of dense, low-temperature plasma. Taylor[11] and Sternleib et al.[12] found that the virtual cathode formed downstream of the anode does not collapse as a space-charge-limited current of ions is extracted from the plasma sheet. Taylor's calculations indicate that most of the ions are accelerated to a velocity corresponding to the potential of the virtual cathode, or about the electron beam energy. Additionally, there is a faster group of ions with energies up to twice the energy of the electron beam.

The simulations show that electron beam propagation without ions is limited to extremely low currents. They also illustrate that electron beam propagation and ion acceleration are dynamic effects and that time-dependent phenomena can be important. For example, the formation of transient virtual anodes in the propagation region is predicted both by the computer simulations and analytically.[12]

The qualitative features of the computer simulations have been rather well reproduced in experiments with relativistic electron beams and dielectric anodes or gas injected into the anode region. Taylor measured constant beam-front velocities about equal to the velocity of a proton accelerated to peak diode voltage and an ion component with energies up to about twice the peak electron energy.[11] Ion bunching has been observed by workers at the University of Maryland, which may represent the effect of transient virtual anode formation.[12]

Many of the features of the one-dimensional computer simulations are also in evidence in our experiments, where neutralization is provided from the walls of the dielectric guide. It is evident, of course, that three-dimensional effects must be important in our and other experiments. The principal discrepancy with Taylor's simulation is the lack of detailed scaling of the beam-front velocity with $E^{1/2}$. A possible explanation of this discrepancy is that the ions, whose "steady-state" velocity

determines the speed of the electron beam front, are launched down the guide before the virtual cathode reaches its maximum potential. All experiments with dielectric guides show an initial delay of several nanoseconds when the beam arrival time-position curves are extrapolated back to the entrance of the guide. This delay is shorter at increased beam energy (see Figure 3-4), an observation also made by Agafonov et al.[6] and Doggett et al.[8] Presumably, this period represents the time to break down the surface of the guide, to inject ions into the potential well of the virtual cathode, and to initiate downstream propagation.

The time for a proton to accelerate from the wall to the center of the guide can be estimated by the quarter-period of a positive ion falling into a homogeneous cloud of negative space charge. It is shown in the Appendix that this time is given by

$$t_{1/4} = \frac{\pi}{4} R \left(\frac{m_i}{2qV} \right)^{1/2} \tag{4.1}$$

R and V are, respectively, the distance and potential difference between the wall and center of the cloud, and m_i and q are the mass and charge of the ion.

In our experiments, the potential represented by protons moving at a front velocity of 5×10^6 m/s is 130 kV, and with a guide radius of 1.9 cm, Eq. (4.1) gives a quarter-period of 3 ns. The observed time delay before propagation was 10 ns or less, so that the beam begins its propagation well before the diode has reached its maximum voltage (see Figure 3-3).

Thus, the velocity of the ions which determine the beam-front speed should depend on the detailed time history of the potential well while the ions are being liberated and accelerated from the walls of the guide. It has been shown theoretically that the instantaneous potential of the virtual cathode in front of a pulsed, space-charge-limited electron accelerator can be greater than the diode voltage[14]. This may account for the observations in which the energy of a proton moving at the front velocity is somewhat greater than the peak voltage on the accelerator (see Figure 2-2).

4.2 TRANSPORTED CURRENT

There seem to be considerable differences between the present experiments and earlier work at Spire and elsewhere on the efficiency of transporting electron beam current in dielectric guides. In our initial experiments with the SPI-PULSE 6000

accelerator and guides made of Lucite or other highly hydrogenated plastics, the transmitted electron current was a large fraction, up to 80 percent, of the injected current pulse soon after the beam front had passed the Faraday cup.[1,7] The loss of the total transmitted charge was about linear with guide length, another indication that beam-front erosion was the principal loss mechanism. Experiments at North Carolina State University also showed high efficiency of current transport once the eroded beam front had passed the current collector.[8]

The researchers at the Lebedev Institute[6] report rather efficient current transport in guides of several different organic and nonorganic dielectrics and conclude that the neutralizing ions come from an adsorbed layer on the surface of the guides. Approximately exponential loss of transported current is observed when the guides are replaced by metallic tubes or when only the inlet of a metallic guide is covered by a short section of dielectric.

In the present experiments, the electron accelerator was fired several times to "condition" the guide after being exposed to air or when there were long delays between measurements. We did note, however, that considerably more current, by factors of two or more, and earlier arrival times, by 5 to 10 ns, were characteristic of the conditioning shots. These shots apparently removed contamination from water and oil from the surface of the guide.

An explanation for the qualitative and quantitative differences between the present and earlier experiments is the high dielectric strength and low degassing rate of the epoxy used for the measurements of beam propagation. Once the adsorbed contaminants were removed during the conditioning shots, there may not have been enough volatile, hydrogenated material released from the surface of the guides to provide complete neutralization of the propagation beam. The velocity of the beam front apparently was not affected by the lack of neutralization behind it; the computer simulations show that the head of the beam needs only partial neutralization to propagate[11].

An exponential loss of current with distance of propagation would represent a constant fractional loss per unit length of guide. Losses of this type could be explained by the results of the computer simulations, which show that the potential well formed by the virtual cathode does not collapse as the partially neutralized beam

propagates away from the source of plasma ions. Electrons from the diode entering the potential well may be retarded and deflected to the walls of the guide, where they flow back to the anode in the plasma layer created by the electrons at the head of the beam.

As discussed in Section 3, there was evidence that the propagating electron beam undergoes strong self-pinching, at least in the vicinity of the Faraday probe. This observation may conflict with our measurements showing important current losses over the length of the guide. However, we saw in Section 3 that the Faraday probe can influence the propagation of the beam, both in the arrival time of the beam front and in the transported current. The perturbations are particularly important when the Faraday probe is less than a guide-diameter's distance from the inlet of the guide. In these experiments it is plausible that pinching occurs only in the immediate vicinity of the probe as a result of neutralizing ions released from the probe and by shorting of the radial electric fields.

SECTION 5
PLANS

During the next year of the program we shall concentrate on experiments to detect collectively accelerated ions and to investigate their processes of acceleration. A low-impedance relativistic electron accelerator, GAMBLE I at the Naval Research Laboratory, will be used to generate a very high current electron beam to test our earlier observations of a strong dependence between ion acceleration and electron current density. Ion acceleration experiments using the SPI-PUSLE 600 at Spire will also be conducted at lower beam energies and currents.

Another series of experiments to test our conclusions on the mechanisms of electron beam propagation in dielectric guides will be initiated using the SPI-PULSE 600 accelerator. An independent method of measuring the beam-front speed will be used to supplement measurements with the Faraday probe, and measurements of current propagation will be made with different guide materials.

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APPENDIX
TIME FOR AN ION TO BE ACCELERATED INTO SPACE CHARGE CLOUD

The equation of motion of a nonrelativistic positive ion accelerated by the electric field of a spherical cloud of negative space charge is given by

$$\frac{d^2 r}{dt^2} + \frac{qen}{3\epsilon_o m_i} \, r = 0 \tag{A-1}$$

where r is the radial position of the ion with mass, m_i, and charge, q; n and −e are the density and charge of the particles of the space charge cloud, t is time and ϵ_o is the permittivity of free space.

If the ion is released from rest at a radius R, it will perform simple harmonic motion,

$$r(t) = R \cos \omega t \tag{A-2}$$

where

$$\omega = \left(\frac{qen}{3\epsilon_o m_i} \right)^{1/2} \tag{A-3}$$

A similar equation can be written for electron clouds of cylindrical or planar slab geometries. In all of these cases, it can be easily shown that

$$\omega^2 = \frac{2q}{m_i} \frac{V}{R^2} \tag{A-4}$$

Where V is the potential difference between the initial position of the ion and the center of the space charge cloud.

The time to accelerate from position R to the center of the cloud is given by a quarter period of oscillation, or

$$t_{1/4} = \frac{\pi}{4} \left(\frac{m_i}{2qV} \right)^{1/2} R \tag{A-5}$$